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BASIC OPERATING LIMITS ON COMMUNICATION LINKS WITH SPACECRAFT

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von Nachrichtenverbindungen mit Raumfahrzeugen".
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ABSTRACT

Space communications can be defined in terms

of information theory, thermodynamics and wireless

energy transmission. Information theory is applicable

if an alphabet is present and if a probability is

associated with each letter of this alphabet. The

concept of information is defined and several examples

are given. The concept of entropy in thermodynamics

is shown to be very closely associated with space

communications. This is due to the fact that each

letter in information theory is made up of fundamental

building blocks which have an entropy associated with

them according to Boltzmann's equation.

The practical limitations of wireless energy trans-

mission show that the maximum communication distance is

$1.14 \cdot 10^{13}$ km, somewhat more than a light year. *author*

Ladies and gentlemen: /1*

There is a class of lecture which has no element of suspense. This

is based on the fact that the lecturer and the listeners are of the same

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Note: Numbers in the margin indicate pagination in the original
       foreign text.

opinion to begin with. Of course, the lecturer is carried by a wave of agreement and his esteem grows, and due to this fact the lecturer is being superfluous. Therefore, I was especially challenged by the invitation to talk before you today. I accepted it with thanks and promise you that I will not talk to you as a conformist. Also, I cannot count on carrying open doors to Athens. For truth's sake, I ask you for your criticism. We would all like to be truthful. If I must use some trains of thought which do not belong to everyday life, I will attempt to present the material to you as simply as possible. That portion of my lecture that is not immediately apparent will be clarified in the following discussion or at a later time.

In this connection, I would like to point to the following ob-   /2
servations. Today's technically-oriented society apparently does not attach a great deal of importance to arguments that are based on theo-   ·
retical fundamentals alone. We all know the type of technical specialist who has very accurately aimed opinions to deal with technical realities, but outside of this domain, nothing is valid, least of all a theory. The opposite is also known. The theoretician for which basically nothing is possible and who, just like the philosopher Hegel, faced with reality, declares in anger that reality is therefore worse off. Due to the nature of my topic, I will have to use primarily theoretical arguments.

The alchemists of the Middle Ages were looking for a wise man's stone, with which one can transform worthless material into gold. Only a genera-tion ago there were patent applications, the nucleus of which was the

perpetuum mobile. Today no scientist will investigate further, if the fundamentals have been thoroughly checked. In this sense the axioms of physics, that is the principal theorems of thermodynamics, as well as the various conservation laws, represent final limits. For clarity's sake, we would like to emphasize that these limits are not given by the formulation of these theorems but are based on the enormous evidence upon which they are founded.

A scientist of today cannot go outside the theorems of physics (Fig. 1). However, the limits of their formulation can change. Even a new theoretical summary does not invalidate the facts which have led to the laws which were valid up to this time.

Theory can even be used as a directive for technical action. In /3 areas, where the distance between the state of technology and the physical knowledge is especially large, it is most advantageous to carry out technical research and development work. When the physical limits have almost been reached, little remains to be gained. If the technical goal lies beyond the physical limits, then this is simply due to the fact that the person who wishes to carry out the work is not aware of this.

Today it is my intention to build a structure that has a certain similarity with the American Consulate in Munich. This structure rests on columns (Fig. 2) and could be inscribed with the words "Space Communication Technology". Before I do this, I would like to show you the three supporting columns by putting together the individual building blocks. We would like to call these columns:

I. Information theory,

II. Thermodynamics,

III. Wireless energy transmission.

I. <u>Information Theory</u>

Information theory is not only a pastime for theoretically-interested communication engineers, of which the old practitioners have the same opinion as the fox did of the dangling grapes in Aesop's fable, i.e., it is of no practical importance. Information theory can always be applied when the following conditions are satisfied (Figure 3):   <u>/4</u>

Condition 1: <u>There must be an alphabet</u>.

This alphabet must be a complete one, and all letters in this alphabet must be clearly distinguishable from each other.

Instead of an alphabet, one can also designate a sequence of marks and symbols. In applications other than those of communication technology, one speaks of an ensemble of occurrences or states - terms which are somewhat more abstract. In terms which are mathematically abstract, one speaks of a collection of disjunctive elements.

Condition 2: <u>A probability must correspond to each letter</u>.

We must therefore eliminate all singular letters, marks, symbols, events, states, such as, for example, a Chinese letter in an otherwise entirely German text - which would seem like lightening out of the blue.

The concept of probability is a very deep one and is not exhausted by the following explanation: let us assume a typist sits at her typewriter in her office in which, day in and day out, only routine material is handled.

It is assumed that individual counters for each letter of the typewriter have been installed (including spaces). Furthermore, let us say that the sum of all typewriter strokes is formed. At each instant of time (let us say with the aid of an electronic computer), the relative abundance is calculated continuously. This relative abundance strives towards a limiting value, which can be identified with the probability using a somewhat coarse simplification.

If these two conditions are satisfied, information theory then <u>defines</u> a piece of information (Figure 4). /5

The concept of information is therefore a definition which is useful and is based on the probability of an occurrence. This information is generated because chance chooses a <u>certain</u> occurrence out of an ensemble of events that can occur. It does not depend on the nature of this occurrence, but only on its probability.

Before a certain occurrence has taken place, it is possible for the observer to evaluate the totality of all occurrences and this according to the expectation value of the information per occurrence. (This expectation value therefore corresponds to the expected probability of winning in a lottery relative to one lottery ticket.) (Figure 5.)

If the occurrences take place one after the other, where each occurrence is individually chosen by chance from the totality of all occurrences, one speaks of a random <u>process</u>. If the randomness does not depend on the preceding events, then each decision generates the same amount of information on the average. The amount of information corresponding to a time interval is therefore z times the expectation value per event on the average, if per time unit z events occur. This quantity is called the information <u>flow</u> and

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indicates what information is generated by an information source – whether it is taken from an information reservoir, flows into a transmission canal, or whether it is received by an information reservoir.

Today it is of importance to note that by introducing this measure of information, it is possible to not only evaluate a continuous sequence of /6 events, but it is possible to evaluate any transmission canal according to its information flux.

Examples: (Figure 6)

1. Suppose an indicating device which is used in connection with the transfer of information consists of a light bulb cover, which is either on or off. Let us say both states are equally probable. If the state during each second is called an event, this device generates a unit of information per second. This information unit is called a bit. The unit of information flow is therefore a bit per second (bit/s).

2. Let a self-indicating digital volt meter have an accuracy of three digits, and let it be driven by an impulse generator, in such a way that a new measured value is established each second. If the probability is uniformly distributed over all possible measurement values, then each measured value contains the information $-ld \frac{1}{1000} = ld \ 1000 = 9.97$ bit. The digital volt meter generates an information flow of about 10 bit/s.

Since the digital volt meter takes the information from a test specimen, it can be also considered as an information canal which has a canal capacity of 10 bit/s.

3. The peak performance of a human being as a member of a communication system (for instance, reading and speaking measured values, taking steno-graphic notes on dictation, playing music according to unknown notes,

reaction to traffic signals) is about 10 bit/s on the average.

4. A telephone network can transmit about 20,000 bit/s. /7

A channel of about 250,000 bit/s is required for high quality music transmission.

The channel capacity of a television circuit is about 50,000,000 bit/s.

The limit of channel capacity of communication systems that are presently feasible should lie at about 10^9 to 10^{10} bit/s. Therefore, it is appropriate to say that the normal requirement of a technical communication channel between a ground station and a space vehicle should have a channel capacity of 10 bit/s, in order to have an appropriate reference value. This amount corresponds to human beings, and means that one measured value is transmitted per second with an accuracy of 1% of full scale. It is always possible to calculate the number of measured values per day or per hundred years.

II. Thermodynamics

I am sure you will be surprised to see that I am departing from the theoretical fundamentals of communication technology and will now discuss the theoretical fundamentals of thermal machines. Please let me pose a rhetorical question: All the important domains of technical science can be found in a physics book. Fulcrum laws, hydraulics, theory of electricity, optics, quantum physics, to name only a few, are key words for the engineer as well as for the physicist. Can you find anything about letters, marks, information, news in a physics book?

It can be said that implicitly something about these topics can be /8 found in any physics book. One must look for this under the word entropy.

The reasons for this will now be shown.

The entropy concept has two different definitions in physics. In the old definition, entropy characterizes a <u>macro</u>scopic state of thermodynamics. For a given amount of ideal gas, entropy only depends on its volume and its temperature, i.e., only on macroscopic quantities. According to Clausius we have

$$\text{Increase in entropy} = \frac{\text{heat introduced reversibly}}{\text{absolute temperature}}$$

(Figure 7). The newer definition according to statistical mechanics of Boltzmann derives the entropy from the probability distribution of the <u>micro</u>physical states (Figure 8). By means of the duel definition, the macroscopic thermodynamic state is reduced to the probability of the micro-states.

It now becomes possible to look upon any mark, any letter, or any other physical state as a distribution of matter or energy in space or in time that is as improbable as possible. If an archaeologist finds some-thing, it would be assumed to have been made by human beings, if it could have been created naturally with only a very small probability. On the other hand, in order to be as safe as possible from random disturbances, we use only those letters which chance cannot easily create by itself. Thus, **our language is distinguishable from the rustling of the wind or** <u>/9</u> the noise of hail. Our writing can be distinguished from random ink spots, at least in the case of adults.

Just as is done in reality, it is possible to look upon a letter/con- ^{as} sisting of considerable smaller individual particles, as is done in infor-mation theory. For instance, let us think of a letter consisting of

individual elementary surfaces, as is the case for a radar receiver (Figure 9).
Similarly, any other mark or process, which we wish to look upon as an
element of information, can be thought of as having been produced by the
ordering of smaller particles that were originally randomly distributed, so
that they finally represent the mark or process in the sense of information
theory. The maximum size that these particles can have usually is in the
range of macrophysics and varies according to the definition of the dis-
tinguishing characteristics between the individual letters in an alphabet.

These small particles, of which the letters are composed, will be
called building blocks. The building blocks can have very different forms,
technically as well as physically. They can actually be small square sur-
faces, which are white on one side and black on the other. We can also
mean small ink particles. Finally, these building blocks can also be rela-
tively small energies that can be moved around the time axis as one desires.

All these building blocks have an entropy according to Boltzmann's
equation. According to a theorem of physics, the entropy, which the building
blocks have together, is the sum of the entropies of the individual building
blocks.

If the building blocks are used to make marks, a macrostructure is   /10
superimposed on the previous microphysical structure. Each of the old micro-
physical states and one of the macro-states, which corresponds to a letter,
results in a new micro-state. The number of micro-states has been increased
from n to n N. An individual pair of events, where x_j coincides with a_i,
has a probability that is equal to the product of the individual probabilities:
$p(x_j)$ $p(a_i)$, according to a theorem of probability theory. If this is sub-
stituted in Boltzmann's equation (Figure 10), it can be seen that the entropy

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has been increased by $\Delta S = k \ln 2\, H$ due to this increased freedom.

This result is of physical importance: a signalling apparatus, with which it is desired to send signals, must of necessity have a mobility, a freedom, which is available to send the signals. This calculation shows that this freedom is also a thermodynamic freedom. It also shows that the expectation value of the information H, which Shannon himself calls entropy, is also an entropy in the thermodynamic sense. Only the scale is different by the factor $k \cdot \ln 2$. Expressed in another way, we can say: the average information per signal in a system is identical to the fraction of entropy contained in it. It can be used to send signals.

Let us go a step further: if information is an entropy in this sense, it must also be an entropy of the macroscopic type, according to Clausius. It must be justifiable to establish the following equation:

$$\Delta Q = kT \ln 2\, H.$$

This means, therefore, the generation of information requires a certain minimum energy which is proportional to the absolute temperature.

At first one thinks that the energy to operate the signal apparatus can be made arbitrarily small. We are not talking of the energy which flows through the signal light, which is used to drive the top bar on the paper, which leaves the vocal cords of the speaker, but we mean the energy which is necessary to activate relays which trigger the release of the signal. The construction of the triggering apparatus can be thought of in any way: there always remains a system which has exactly the freedom ΔS or H which is required according to theory. This freedom is also a thermodynamic freedom.   Each degree of freedom has an energy corresponding to the temperature. If the key in question is too loose, it will carry out Brownian motion. The

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signalling apparatus begins to play by itself and produces nonsense. If, on the other hand, a safety mechanism is provided, which must be done because otherwise the apparatus will no longer transmit any information, then it is required that the energy necessary to activate the apparatus be such that it can overcome the safety mechanism.

Any other disturbance that reaches the channel or influences the keys will be of exactly the same random nature. It is appropriate to express the disturbing energy, regardless of its origin, by means of the equivalent temperature. If the disturbance sources are independent, it is necessary to substitute the sum of all substitute temperatures for T in the equation. <u>/12</u>

The fact that each radiation leads to quanta if the energy is extremely small must not be overlooked. In this case, the developments presented so far are not automatically valid: even an ideal receiver in the absence of any disturbances could do no more than count individual quanta. The information is then derived from the probability of the occurrence of a quantum number. This limit can be brought into the present discussion by establishing a correspondence between the quanta and a substitute temperature $T = \dfrac{h\,f}{K}$. By substituting the value of the Boltzmann constant, this results in

$$T = 4.8.10^{-11}.f \,{}^{\circ}K .$$

It is then seen (Figure 11) that the equivalent temperature can not go below a lower limit, even if an ideal receiving station, wich is not technically possible at present, is built on the moon: a basic background noise remains, which is composed of the quantum noise and the noise coming from the galaxy, and which amounts to about $5\,{}^{0}K$. This limit can also be expressed in another

equivalent way: the ideal receiver counts individual quanta, where the quanta are not only sent out by the transmitter, but also in part by the galaxy.

In the case of communication links from the earth to the space vehicle, this substitute temperature is about equal to the temperature of the Earth's surface.

Thus, the problem of transmitting information under extreme conditions is reduced to the problem of sending energy over great distances without the use of wires. According to the numbers given, each bit of information re- /13 quires an energy of at least $5 \cdot 10^{-23}$ watt seconds. This is an absolute physical limit, which is based on the second principal theorem of dynamics. The chances that a future technical advance will overcome this limit are no larger than the chances of a perpetuum mobile of the second kind.

III. Wireless Energy Transmission

The only remaining question left should be answered by conventional high frequency technology: how large is the largest distance R from which a certain power $N_e = \frac{\Delta Q}{t}$ can be directed towards the receiver per unit of time?

As could be expected, the answer to this question depends on the present state of technology. Certain antenna dimensions and performances of the transmitter are substituted. Since one can expect technical advances in this field, it is not possible to give a sharp upper limit. This does not mean that such a limit does not exist, at least in the asymptotic sense. I mean the following: all technical achievements are limited by the dimensions and the amounts of material and energy, which are basically available

to man. Maybe man can build a cm-wave antenna of the size of a football field, but not an antenna that can cover the lake of Constance or Bavaria. If one would require an antenna whose radius is, let us say, equal the distance to the moon, then this quantity will lie beyond an asymptotic limit for the antenna dimensions.

Similar reasoning can be carried out for the output of the trans- mitters. The technical possibilities will cease somewhere, especially if we are discussing a range over several orders of magnitude.

I would, therefore, like to proceed in the following way: in order to get a feeling for the orders of magnitude, I will calculate an example, for which parameters have been substituted, which today must be called technically utopian. Let the specialists say how many powers of ten – higher or lower – they want to establish the asymptotic limits. Then it is possible to calculate the corresponding limiting range.

From Figure 11, it is seen that the most advantageous frequency lies in the vicinity of 10 Gc. Furthermore, I assume ideal transmission and receiver antennas. By this, I mean antennas which have no losses, because the losses result in a disturbance corresponding to their temperatures. Furthermore, these antennas have directionality gains, corresponding to t he absorption surfaces F_e and F_s.

The following parameters are substituted:

Wavelength: λ = 3 cm = 0,03m,

Transmitter power averaged over time: N_s = 10,000 watts,

Absorption surfaces of the transmitting antenna: F_s = 100 m^2,

of the receiving antenna: F_e = 10,000 m^2.

Under these assumptions, the received power according to a well-known theorem of high-frequency technology is

$$N_e = \frac{F_e\,F_s}{(4\pi\lambda)^2} \cdot \frac{1}{R^2} N_s \quad,$$

where R is the distance in meters. If the numbers are substituted and by reducing the result by six powers of 10, in order to express the distance in kilometers, one obtains

$$N_e = \frac{5.7 \cdot 10^4}{R^2} \quad . \quad \text{(R in km)}$$

If one requires a power of $5 \cdot 10^{-22}$ watts corresponding to an information flow of 10 bit/s, the limiting distance is

$$R = 1.14 \cdot 10^{13}\text{km} \quad,$$

that is, something more than a light year.

As a comparison let us give the following astronomical distances:

Pluto is of a distance of about $6 \cdot 10^9$ km. the nearest fixed star system is at a distance of about 8 light years. Our galaxy has a radius of about 50,000 light years. The nearest galaxy is about 10,000,000 light years away. Entire space has a radius of about 10,000,000,000 light years.

Final Summary

I would like to give the final summary in the discussion. I would like to say that, according to the numerical values of the parameters I have used, ten powers of 10 in distance are missing. It would be necessary to correct the quadratic distance law by about twenty powers of 10 by changing the

technical data, in order to have all-encompassing space technology based
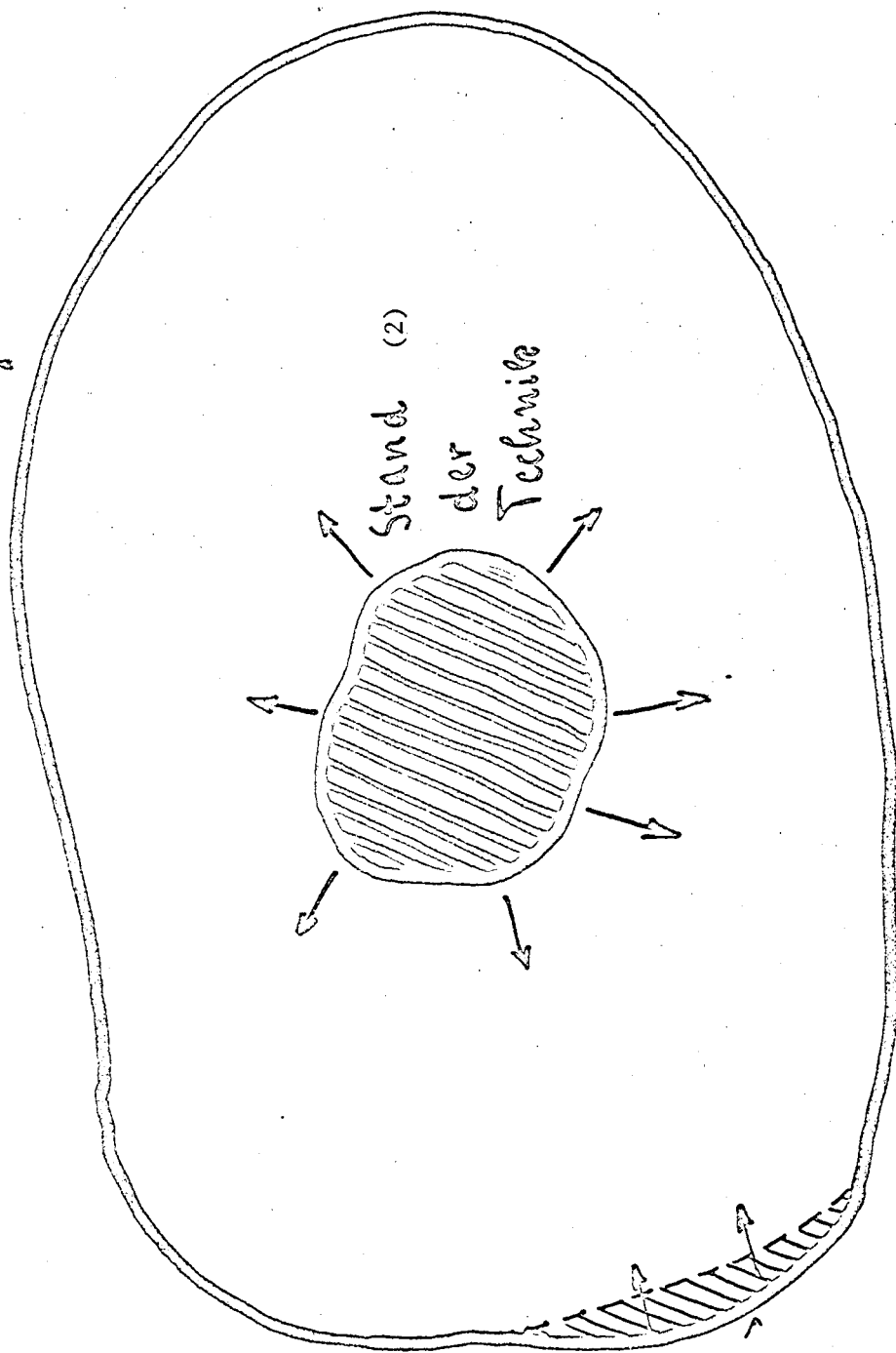on communications.

On the other hand, this article has shown the technical possibilities
that exist to research our planetary system and even the space that is
a little bit beyond this. But it looks as though we cannot plan on
visiting the nearest fixed star and its planetary system.

REFERENCES

1. Szilard, L. The Entropy Decrease in a Thermodynamic System When
   Intelligent Beings Intervene (Über die Entropieverminderung in einem
   thermodynamischen System bei Eingriffen intelligenter Wesen). Z. f.
   Phys., 53, 840-856, 1929.

2. Brillouin, L. Science and Information Theory. Academic Press Inc.,
   New York, 1956.

3. Fano, R. M. Transmission of Information. J. Wiley, New York, 1961.

4. Baghdady, E. J. Lectures on Communications System Theory. McGraw-Hill,
   New York, 1961.

5. Peters, J. Range of Validity and Application of Information Theory
   Outside of Communication Technology (Geltungsbereich und Anwendbarkeit
   der Informationstheorie ausserhalb der Nachrichtentechnik). NTZ, No. 12,
   621-625, 1963.

6. Hoerner-Schaifers. Meyers Handbook on Space (Meyers Handbuch über das
   Weltall). Bibliographisches Institut, Mannheim, 1960.

Figure 1

(1)- Physical Limits
(2)- State of Technology
(3)- Physical Progress

Raum-Nachrichtentechnik (1)

Informations-theorie (2)

Thermo-dynamik (3)

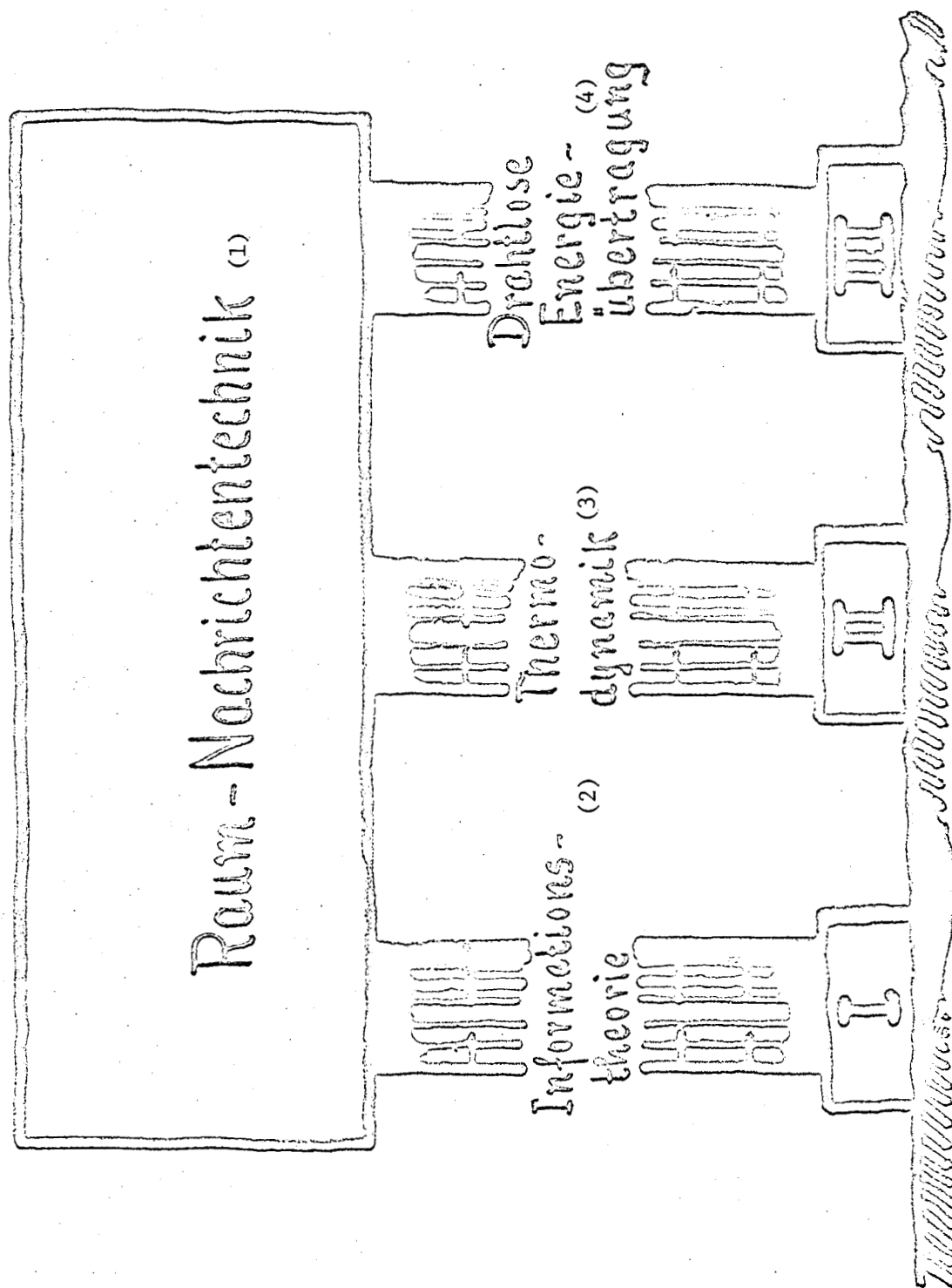Drahtlose Energie-übertragung (4)

Figure 2

(1)- Space Communication Technology; (2)- Information Theory; (3)- Thermodynamics;
(4)- Wireless Energy Transmission

Information theory is always applicable, when the following conditions <u>/16-c</u>
are fulfilled:

1. <u>There must be an alphabet</u>: $a_1, ..., a_i, ..., a_N$

    Instead of alphabet, one can also speak of an ensemble

    of states or collection of events.

2. <u>A probability must correspond to each letter</u>: $p(a_1), ..., p(a_i), ..., p(a_N)$

    Instead of letter, you can say: Mark, Symbol, State, Event, etc.

Information is a quantitative term; by means of a <u>definition</u> it is derived <u>/16-d</u>
from probability numbers.

If chance chooses a certain event (a_i) from the totality of all events
$(a_1, ..., a_i, ..., a_N)$, then it generates the information

$$-\text{ld } p\ (a_i) = \text{ld } \frac{1}{p(a_i)}$$

by this decision.

ld = logarithmus dualis

The events $a_1, ..., a_i, ..., a_N$ are brought into definite correspondence with <u>/16-e</u>
the information values $-\text{ld } p(a_1), ..., -\text{ld } p(a_i), ..., -\text{ld}(a_N)$. Therefore,
they appear with the same probability as the events themselves.

The expectation value for the information per event is therefore

$$H = -\sum_{i=1}^{N} p(a_i)\ \text{ld } p(a_i)$$

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Examples for information flow in practice:

1. One yes-no decision per second = 1 bit/s.

2. A digital volt meter which has 3 decimal positions per second
    results in <u>10 bit/s</u>.

3. A human being as a link in a communications system follows up to
    a rate of about <u>10 bit/s</u>.

4. Technical communication channels:

    Telephone circuit: about 20,000 bit/s

    Music transmission: about 250,000 bit/s

    Television: about 50,000,000 bit/s.

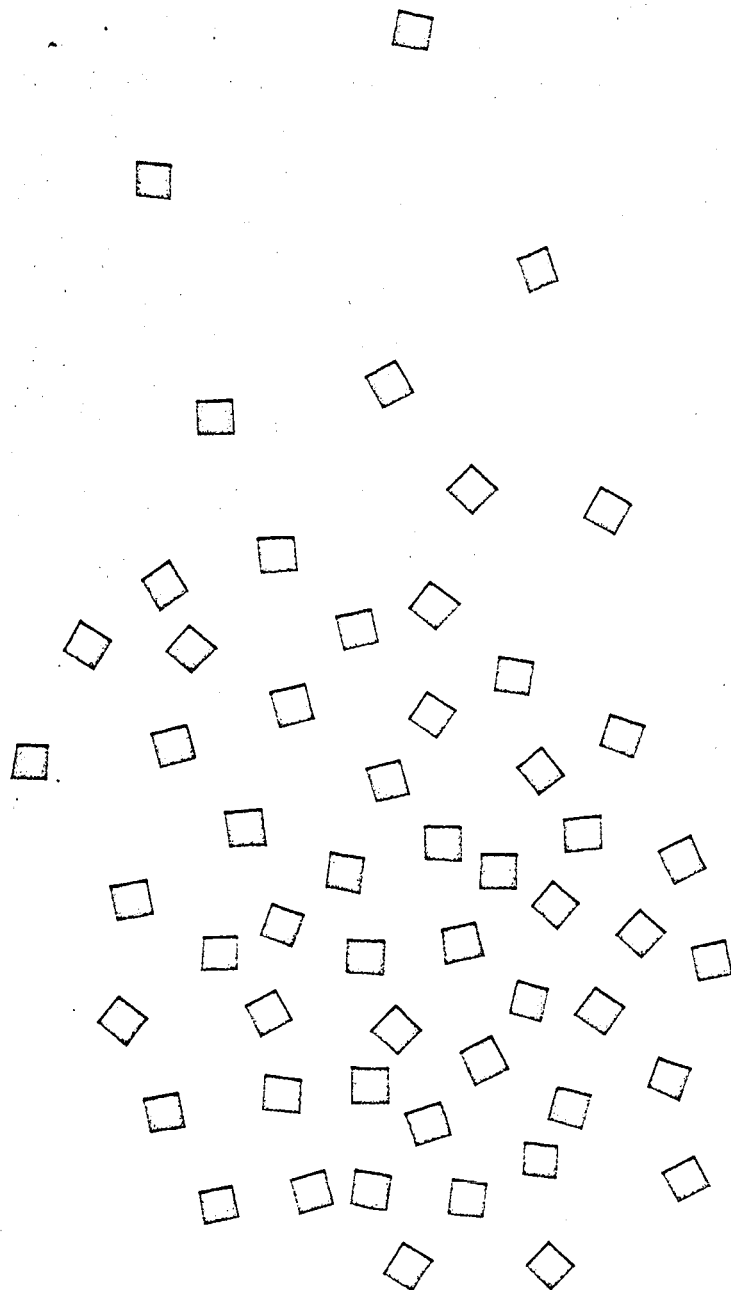The entropy is a thermodynamic state quantity according to Clausius.

An increase in entropy by ΔS occurs, when

$$\Delta S \ = \ \frac{\Delta Q}{T}$$

in which

ΔQ is the reversibly applied heat and T is the absolute temperature.

Ungeordneter (1)
Zustand
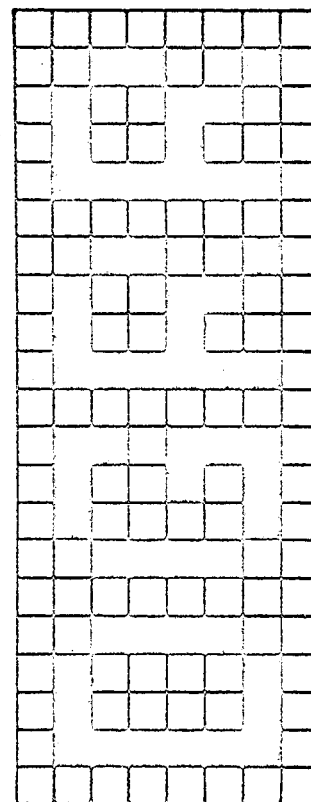
Geordneter (2)
Zustand

(1)– Non-ordered State
(2)– Ordered State

Entropy, according to Boltzmann, is calculated from the probability

distribution of the microphysical states (X_j). It is

$$S = -k \sum_{j=1}^{n} p(X_j) \ln p(X_j)$$

The states that can be distinguished from each other are $X_1 \ldots$, $X_j \ldots$

$\ldots$, X_n. In the equation, k is the Boltzmann constant

$$k = 1.38 \cdot 10^{-23} \text{ Ws/}^{\circ}k.$$

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By superposition of the macroscopic randomness, the number of micro-

physical states in the building blocks becomes: n.N. Each of these states

has a probability: $p(X_j) \cdot p(a_i)$. The equation of Boltzmann gives the

entropy:

$$S + \Delta S = -k \sum_{j=1}^{n} \sum_{i=1}^{N} p(X_j) p(a_i) \ln [p(X_j) p(a_i)]$$

$$= -k \sum_{j=1}^{n} p(X_j) \sum_{i=1}^{N} p(a_i) \ln p(a_i) - k \sum_{i=1}^{N} p(a_i) \sum_{j=1}^{n} p(X_j) \ln p(X_j)$$

$$= k \cdot \ln 2 \cdot H + S;$$

$$\Delta S = k \cdot \ln 2 \cdot H.$$

/16-k

(1)- Galaxy; (2)- Equator; (3)- "quiet" sun;
(4)- Pole; (5)- Earth's Atmosphere; (6)- Receiver;
(7)- Theoretical Limiting Value; (8)- Equivalent
Temperature; (9)- Gc

„ruhige" Sonne (3)

(1) Galaxis

Äquator (2)

(4) Pol

Erdatmosphäre (5)

$0°$

$~90°$

(6) Empfänger

Theoretischer
Grenzwert (7)

(8) Äquivalente
Temperatur

$$T = \frac{h \cdot f}{k}$$

GHz (9)

0,001   0,01   0,1   1   10   100   1000